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Cirrus cloud over Southern England

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Summary

Data are presented of the frequencies of occurrence of cirrus cloud over Southern England, diurnal and seasonal variations, types of high cloud, heights and temperatures of bases and tops, thickness, visibility, and humidity in its vicinity. These data are based on surface observations and four years' high level ascents by aircraft of the Meteorological Research Flight. Details of the formation temperatures of condensation trails and the relation between their persistence and the presence of high cloud are given. Finally some mechanisms are suggested for the formation of high cloud over the British Isles.

Introduction

Although high cloud when visible from the ground is reported in all synoptic observations and is plotted on synoptic charts, very little is known of its physical characteristics and the conditions under which it occurs. In the past cirrus cloud has been regarded of little practical importance compared with other types but with the advent of regular flying at cirrus levels its importance is increasing. A study has therefore been made of the observations of high cloud taken during the high level ascents made by the Meteorological Research Flight from 1949-1952. These ascents were made primarily for the purpose of measuring temperature and humidity up to about 40,000 feet with cloud observations as a secondary consideration. Details of the measurements of temperature and humidity made up to 1951 are summarised in Ref.1. In 1952 particular attention was given to the high cloud observations during the flights made by one of us (P.G.) and this led to some of the conclusions given below which were also found to be consistent with the earlier observations. In addition to these flight observations use has also been made of ground observations made at the synoptic stations of South Farnborough, Shawbury, and West Raynham. A preliminary study has also been carried out on the relationship between some of the high cloud observations and the surface and upper synoptic charts for the same period.

Part 1. Information derived from surface observations

Surface observations of cirrus possess severe limitations. It is frequently impossible to see high cloud owing to the presence of lower clouds or fog, and observations at night are very difficult indeed. Haze layers in

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the atmosphere also have an effect. It has been noticed frequently during the flights that the amount of cirrus visible increases as the aircraft ascends and it may sometimes even happen that there is eight-eighths of thin cirrus present when none is visible from the ground. As the aircraft penetrates the thick surface haze top this increase is sudden. In addition the sun's elevation appears to be an important factor in the visual recognition of the cirrus from the surface. Nevertheless a survey of surface data on cirrus is of interest and is given below.

In Fig.1 mean frequencies throughout the day of surface observations of high cloud are shown for each month for the period 1944-52 at South Farnborough. In Fig. 2a a comparison of the daylight observations of high cloud at South Farnborough, Shawbury, and West Raynham for the years 1950 and 1951 is given. Fig. 2b is a similar diagram for daylight observations at South Farnborough only for the longer period 1944-52.

Considering Fig.1 it is seen that:-

(i) The observations all have a pronounced diurnal variation. During daylight hours cirrus is reported on an average for about 30% of the time and during the night 15% of the time.

(ii) During the winter months the cirrus observed curve rises during the morning twilight period, reaches its maximum within an hour or so, remains fairly constant throughout the day and then falls again at dusk.

(iii) During the other seasons and particularly in summer there is a peak shortly after dawn and a much larger peak around dusk. Between them there is an unsteady rise which is more pronounced in the afternoon.

(iv) The high cloud obscured curve usually has a maximum around the dawn period and a minimum around the dusk period which is less pronounced in winter. On an average the high cloud is obscured for abount 60% of the time in winter and 45% in summer.

(v) Clear skies with no cirrus were reported for about 20% of the time in daylight and 40% at night.

It is difficult to decide to what extent these observations are real. The belief that the summer dusk and dawn peaks are a visual effect is however supported by the lack of definite peaks in winter when the sun is always low. The large percentage of cases when high cloud is obscured makes it difficult to ascribe any frequency to the periods when cirrus is in fact above the station.

Considering now Figs. 2a and 2b.

(i) The curves of observations of cirrus from the surface all show maxima in the summer when values of about 40% are reached. Values of about 25% are given for all months between October and May.

(ii) The no-cirrus observations show maxima of about 25% in spring and early summer with minima of 15% in winter, with irregular fluctuations in the late summer and autumn.

(iii) The high cloud obscured curve shows a maximum of about 60% in winter and a minimum of 40% in summer. It is interesting to note that in spite of this a secondary no-cirrus minimum is found for August and September.

(iv) In Fig.2 a the curves for the three stations correspond extremely well. This would be expected as the scale of the synoptic types affecting Southern England is in general larger than the area enclosed by

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these three stations. This is in agreement with our aircraft observations and also from examinations of surface synoptic charts which indicate that cirrus sheets are very frequently extensive and indeed sometimes cover almost the whole of the British Isles.

(v) The overall ratios for the period of cirrus occasions to no-cirrus occasions for these stations are as follows:-

Shawbury 2.5, West Raynham 1.8, South Farnborough 1.4.

The possible explanations for this are that

(a) On the average cirrus is more likely in the west than in the east of Southern England.

(b) As Shawbury is near hills the differences may be the results of orographic lifting (Ref.2).

(c) The observations may not be representative of the actual high cloud distribution. For instance haze in the atmosphere may account for these differences.

Unfortunately there is no quantitative data available on the effective obscuration of high cloud by haze at these stations so that little can be said about (c) except that West Raynham has probably suffered most from this effect. The question of when orographic cirrus can form and the likelihood of cirrus being more frequent in western than in eastern districts of the country is discussed in Part 3 below from which it is concluded that both of these explanations could contribute in part to the high cirrus frequencies at Shawbury.

During this work a study was also made of the frequency of the various types of cirrus cloud which were reported over the same period at these stations and the results are given in Table 1.

TABLE 1. Frequency of surface reports of high cloud types

Cirrus Code Number	Short description	% Frequency of type reported			
		South Farnboro'	Shawbury	West Raynham	Mean
1	Ci filaments scattered not increasing	22	16	30	23
2	Ci dense patches usually not increasing	38	32	30	33
3	Ci anvil type associated with Cu Nb	11	12	8	10
4	Ci often hook-shaped, increasing and thickening	1	1	1	1
5	Ci and Cs often in bands increasing but below 45°	2	7	4	4
6	Ci and Cs often in bands increasing above 45°	8	9	9	9
7	Cs covering whole sky	4	6	6	5
8	Cs not increasing not $^{8}/_{8}$	10	10	9	10
9	Mainly Cc	5	6	2	4

Types 1 and 2 are evidently reported with great frequency and Type 4 hardly at all. Types 5 and 7 are also very infrequently reported.

/Part 2.

Part 2. Information derived from aircraft observations

(a) General description. To an observer flying in cirrus the cloud appears as a white haze. The density varies considerably and is usually greatest when the cirrus is a continuation of medium cloud. Frequently the observer is not certain whether he is in cloud or not and the isolated tufts or patches (Types 1 and 2) which are so often reported in observations from the ground seldom occur. Generally the cirrus exists in widespread sheets and these patches appear to be local increases of cloud density. The base of the cloud is usually very ill-defined and it often has streaks falling from it but the tops can be recognised more easily and it appears often that the cloud is more dense near its tops than near its base. A wave-like structure is frequently seen in the tops. Streaks have occasionally been seen coming out of the tops of the cloud but they were comparatively small and short lived.

(b) Frequency of occurrence. The aircraft observations 1949-1952 were as follows:-

TABLE 2. Total aircraft observations of high cloud

	No. of occasions	Percentage
High cloud in the immediate vicinity	112	46
High cloud visible in the distance	65	27
No high cloud observed	66	27
Total	243	100

There is no reason to suppose that these observations are selective in any way so that it appears that for about 50% of the time in daylight there is high cloud above any station in Southern England and that for only 25% of the time are there large areas completely clear of cirrus cloud.

If we subdivide these observations into seasons Table 3 is obtained.

TABLE 3. Seasonal observations of high cloud from aircraft

	Percentage of occasions			
	Cirrus	Distant Cirrus	No cirrus	No. of cases
Winter	58	10	32	41
Spring	31	27	42	68
Summer	50	33	17	70
Autumn	47	31	22	64

Unfortunately the number of winter cases is considerably less than that of the other seasons. However it appears from this table that cirrus is more frequent in summer and autumn than in winter and spring. This is in fair agreement with the data given from surface observations shown in Fig.2a and 2b.

(c) Height of base. It has been mentioned above that the base of high cloud is very indefinite and during an ascent into it the observer notes three successive stages: (i) definitely in clear air below,

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(ii) in a region of doubt "Is the aircraft in cloud or not?" (iii) now definitely in cloud. The region of doubt may in some cases extend through several thousand feet.

In Fig.3 a frequency distribution of heights of cirrus at stage (iii) is given. The values given may therefore be somewhat on the high side but are correct for all practical purposes.

It can be seen that the base of high cloud is most frequently between 25,000 and 30,000 feet and that it is usually somewhere between 20,000 and 40,000 feet in the troposphere. However there have been occasional reports of cirrus in the stratosphere. A height of 46,500 feet has been reported in Ref.3 and on a few occasions M.R.F. aircraft with a ceiling of about 40,000 feet have failed to reach the base of cirrus seen during an ascent. As these observations are of particular interest they are listed below, together with some other observations of cloud in the stratosphere made by other aircraft based at South Farnborough.

Date	Time	Aircraft	Height of Tropopause (feet)	Maximum height of Aircraft (feet)	Estimated height of cloud base (feet)	Description of cloud
4.5.53	1500Z	Mosquito	39,000	35,000	-	Some Cs well above 35,000' may be in the stratosphere.
5.5.53	1000Z	Mosquito	38,000	41,000	45,000	Thick dense extensive Cs.
1.7.53	1600Z	Valiant) Canberra) Meteor)	38,000	-	-	Cumulonimbus top at 42,000'.
27.7.53	1400Z	Meteor	28,000	40,000	-	Some Ci above 40,000' at about 30 miles west of Farnborough.
29.7.53	1200Z	Canberra	34,000	42,000	-	A small amount of Ci or contrail above to the north of Farnborough.
30.7.53	1500Z	Mosquito	35,000	38,000	45,000	A layer of thin Cs to the SW of Farnborough.
7.8.53	1500Z	Mosquito	36,000	39,000	45,000	Thin Cs thickening.

(d) Height of tops. On most of the occasions examined the high cloud appeared to extend to the region of the tropopause. In view of the variability of tropopause height it was therefore attempted to relate high cloud tops to tropopause level. This has been done in Fig.4.

It appears that the tops of the cirrus cloud are most frequently less than about 2,000 feet from the tropopause. It is not known to what extent this conclusion is determined by the nature of the definition of the tropopause, but in practice it appears that the first definite decrease in the lapse rate in the tropopause region determines the tops of the cloud. A few cases have been reported when the tops apparently

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extend into the lowest 2,000 feet of the stratosphere. On other occasions the tops may be as much as 11,000 feet below the tropopause. In these cases the cloud is often patchy, in contrast to the usual widespread effect and resembles patchy altostratus in appearance and density.

(e) Cloud thickness. A frequency distribution of cloud thicknesses is given in Fig.5. Cirrus cloud most frequently has a thickness between 3,000 and 5,000 feet but thicknesses up to 12,000 feet have been observed. Sometimes it merges with the medium cloud. When the thickness is great there is a tendency to layering, but it is difficult to decide whether in fact clear lanes exist with cirrus above and below or alternatively there merely is a stratification of cloud density.

(f) Relationship between the height of the defined tropopause and the base and thickness of cirrus cloud. Fig.6 shows a plot of all the observations of base and top height plotted against the height of the tropopause. Although the number of observations for each of these heights is small and their scatter is large an attempt has been made to draw lines of mean base and top levels for each tropopause height. The following tentative conclusions are drawn from these lines:-

(i) The mean tops appear to reach the tropopause for heights up to 30,000 feet but at higher levels they progressively become relatively lower until at 40,000 feet they are on average about 4,000 feet below the tropopause. It is considered that this happens because as the tropopause height increases, so does the chance of an abrupt slackening of the lapse rate in the high troposphere become greater resulting in the limitation of the cirrus tops.

(ii) The mean bases tend to be at a constant thickness below the tropopause up to a tropopause height of 30,000 feet. At higher levels however the mean base appears always to be in the region of 30,000 feet. Consequently on the average, mean cloud thickness with tropopause levels below 30,000 feet is about 4,000 feet and it progressively increases to 7,000 feet with a tropopause level of 40,000 feet.

We would emphasize that the above conclusions refer only to mean values. Individual cases as can be seen from the scatter of the points on the diagrams may differ widely from them.

(g) Temperature of base and tops. A frequency distribution of temperature of the base of high cloud is given in Fig. 7. The most frequent values are from -40 to -50°F. but measurements have been made within the range -10 to -80°F.

The corresponding frequency distribution of cloud top temperatures is given in Fig.8. This distribution is rather flat between temperatures of -40 and -75°F. but a few values have been measured between -20 and -30°F. and down to -100°F. The lack of temperatures between -30 and -40°F. is interesting and suggests that the few values between -20 and -30°F. belong to another distribution - the low cirrus which is very similar to medium cloud.

The temperature of -40°F. is about the mode of the base observations and there are very few observations of high cloud tops at temperatures greater than -40°F. This is also the temperature given by many laboratory investigators at which spontaneous nucleation becomes effective. If there is a paucity of ice-forming nuclei at high levels as appears likely (Ref.4) it could easily happen that the majority of

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cirrus forms at -40°F. or below without the assistance of these nuclei and that subsequent or self nucleation could lower the bases to include higher temperatures.

The possibility of formation of cirrus cloud however includes considerations of the moisture available as well as the likelihood of nuclei being present and this point is considered in a subsequent paragraph.

(h) Humidity in and around high cloud. A frequency distribution of depression of frost point relative to air temperature as measured with the visual pressurised Dobson-Brewer hygrometer during the periods when high clouds were reported is given in Fig.9. The values used in each case were the minimum depression of frost point within or near the cirrus layer, the readings being taken at 1,000 feet intervals. It has previously been thought that at very low values of frost points the uncertainty of measurement was only about 4°F., and the accuracy somewhat better in cirrus cloud. Recent flights with automatic hygrometers at cirrus levels however have shown that short period fluctuations in the frost point of 5 to 10°F. within distances of less than a mile are common. It is impossible to measure these fluctuations with the visual type of instrument which only gives a mean value over a distance of several miles.

The air temperature can probably be measured to about 1°F. at these levels. Hence it appears from the measurements with the visual instrument that in the immediate neighbourhood and even within cirrus cloud the air is not always saturated with respect to ice but that on an average there is a frost point depression of about 3°F. (about 80% relative humidity), and that lower values of relative humidity are common. However, according to Ref.4, saturation with respect to water i.e. considerable supersaturation with respect to ice is necessary for cirrus cloud formation.

It has also been noted that it is possible to form condensation trails in an atmosphere 60% to 80% saturated and unless cirrus cloud is present these trails almost invariably disappear within minutes. Furthermore it appears likely on theoretical grounds that ice crystals of the size measured in cirrus cloud would evaporate within times of this order in an atmosphere only partially saturated. Hence there is a difficulty in explaining why cirrus cloud should persist at all if these conditions were constant. The fluctuations revealed by the automatic hygrometer may be sufficient to provide regions of supersaturation. Further data is required before these comparatively low mean values of humidity can be reconciled to the long period of persistence of the cirrus cloud sheets as a whole.

(j) Humidity distribution when high cloud is present - the "Moist Layer". When high cloud is present or upwind in direction the distribution of frost points with height usually exhibits the characteristic form shown in Fig. 10a. This example was selected from the "cirrus in the distance" cases, and shows a rapid increase of humidity at 28,000 feet with a moist layer persisting to 32,000 feet, the height of the tropopause. This "moist layer" becomes more pronounced as the distance from the cirrus is decreased until, when cirrus is present near the aircraft, the sounding takes the form of the example in Fig. 10b. The moist layer is not always easy to trace and its depression relative to the dry bulb temperature may be as much as 15-20°F., but this depression quickly decreases as the cloud approaches. When no cirrus is observed the sounding frequently takes the form shown in Fig. 10c. A network of ascents giving this type of information would thus be invaluable to a forecaster who is required to give detailed information on high cloud.

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It is necessary at this stage to qualify the above remarks on account of the different ways in which cirrus cloud may be formed. This is discussed further in a subsequent section. It appears that most cirrus occasions arise when a warm ridge of air recently over the Atlantic is advected over the British Isles at cirrus levels. Other cirrus occasions however arise associated with cold pools or strong convection and the moist layer is not then evident.

Regarding the moist layer as potential cirrus cloud and plotting all the bases and tops relative to the tropopause Fig.11 was obtained. The tops of the moist layer tend to coincide with the tropopause for low tropopause heights but become somewhat lower as the latter increases. Mean moist layer bases tend to have the same distribution with height as the cirrus bases shown in Fig.6 and never exceed 30,000 feet. Consequently mean thickness also increases with height.

As the mean base is about 30,000 feet and its extreme value rarely below 24,000 feet its temperature is generally between -25° and -45°F. Similarly the tops are rarely below 30,000 feet - i.e. at a temperature of -45°F. Hence, as has already been stated in paragraph (g) above, high cloud is potentially always able to form at temperatures below -40°F. and therefore it does not seem necessary to postulate the presence of ice nuclei at cirrus levels in order for the cloud to form.

Cirrus cloud is much more frequent than medium cloud. It appears that this can arise both from the fact that the necessary moisture is more often available at the higher levels and also from the fact that at medium cloud levels temperatures are higher and therefore require some form of nuclei to assist in the condensation process.

(k) Visibility through high cloud. No observations of visibility in cirrus are recorded, but the following details are based on the experience of flying in high cloud.

High cloud usually limits the visibility from air to ground but only when the high cloud is a continuation of medium cloud is it likely that the surface will be completely obscured. Normally the ground (or low cloud) is still clearly visible for several miles ahead when the aircraft is flying in high cloud, indeed sometimes the cloud is so thin that its presence makes little or no difference to vertical visibility. However, vertical visibility is often more limited when the aircraft is above the high cloud. This effect is similar to that of surface haze; when flying just above surface haze the ground is often more indistinct than when actually in the haze layer.

The horizontal visibility in high cloud is a more difficult factor to estimate, but when aircraft of the M.R.F. have been formating in high cloud, although the horizontal visibility was more limited than in clear air, this limitation was not serious and no difficulty was experienced.

Part 3. Notes on the forecasting of (a) high cloud and (b) condensation trails

(a) High cloud.

(i) At present a forecaster has not many tools which help him to forecast the probable occurrence of cirrus cloud. The classic model of fronts, particularly warm fronts, provides one type of phenomenon which may be associated with high cloud. However it is apparent from daily examination of synoptic charts that the presence of the front is neither a necessary nor a sufficient criterion to use. High cloud frequently occurs without being associated with fronts and on the other hand surface fronts need not extend to cirrus levels.

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It is the purpose of this section to suggest other factors which can usefully be taken into consideration when it is necessary to provide a forecast of high cloud.

(ii) The general character of the weather at any point in the lower troposphere is determined by the nature of the air masses involved and the fronts which occur at their boundaries. It is not easy to extend the idea of air mass to cirrus levels but it is usually possible to gain an idea of the recent history of the air there by studying the 300 mb. contour charts. Thus to some extent we can say that the air over the British Isles at 300 mb. is of recent polar or Atlantic track, although of course borderline cases are frequent. It would perhaps be more profitable theoretically to discuss the air characteristics at this level in terms of the position of the long wave pattern with relation to the area involved but this may not be easy in practice as shorter wave phenomena no doubt would be important as regards cloud formation.

It is considered that air at 300 mb. which has had a recent polar history is in general more likely to be free of cirrus than air of a recent Atlantic history. This conclusion is supported by (1) a short study of high cloud frequency with respect to wind direction at cirrus levels and (2) an examination of the moisture content at these levels with respect to the recent history of the air. Describing these now in turn:-

1. From considerations of the relationship between cirrus occurrence and the 300 mb. wind direction.

Over the two years 1950-1 all surface observations from South Farnborough of sky obscured, no high cloud, and high cloud present have been counted for winds in the eight sectors of the compass. The wind directions used were the generally prevailing directions given by the Larkhill ascents between about 20,000 feet and the tropopause. As the ascents were six-hourly and the cloud observations hourly the wind direction was assumed to remain in a given octant for the three hours preceding and following an ascent.

The results are given in Table 4 which shows the percentage of occasions for each octant in which the sky was obscured, there was no high cloud and high cloud was observed.

TABLE 4. The relationships of high cloud observations to prevailing wind direction in the upper troposphere

Wind directions	000° - 040°	050° - 090°	100° - 130°	140° - 180°	190° - 220°	230° - 270°	280° - 310°	320° - 350°
	Percentage of occasions							
Sky obscured	51	64	59	62	55	52	49	52
No high cloud	39	32	34	22	20	23	27	32
High cloud	10	4	7	16	25	25	24	16
Ratio $\frac{\text{high cloud}}{\text{no high cloud}}$	.3	.1	.2	.7	1.3	1.1	.9	.5

From this table it appears that the percentage of high cloud occasions is greatest when the wind is in the SW to W sectors and least in the NE to E sectors. The percentages of no high cloud exhibit the reverse trend.

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Considering the ratio of high cloud to no high cloud it is seen that, irrespective of the fact that westerly winds at 300 mb. are much more frequent than easterly winds at that level, the westerly winds are more likely to produce cirrus. It may be noted also that as easterly winds which are mainly continental in track are unlikely to produce cirrus it is very improbable that nuclei of continental origin are of any importance as regards the production of cirrus cloud over Southern England.

2. From considerations of the recent history of the air at cirrus levels and moisture available.

From the high level ascents made by the Meteorological Research Flight and the relevant 300 mb. contour charts it appears that air at cirrus levels which can be associated with contours extending over large areas of the Atlantic usually has the requisite moisture content. In fact out of the 126 "moist layer" cases found, 106 were in air with a recent Atlantic track, 12 with a recent track over polar regions and 2 with a continental track. There were 9 Atlantic, 12 polar and 2 continental cases with no moist layer. In addition there were about 30 cases with very low tropopauses or cold pools whilst a number of ascents had to be rejected from this study for lack of data. Air streams of recent polar and continental history frequently do not have sufficient moisture at these levels. Hence on this account most cirrus is likely to be associated with air of recent Atlantic history.

(iii) Although it is thought that the recent history of the air exerts a considerable influence on its potentiality to form high cloud other factors which may tend to produce the necessary ascent to bring about condensation must receive full consideration when producing a forecast. A complete list of these factors has not been produced but those which appeared most important from a short study of synoptic cases for the British Isles in 1952 are as follows:-

1. The presence of a jet stream over the area.

2. Warm advection at cirrus levels.

3. Cold pools at cirrus levels.

4. Cirrus formation from tops of cumulonimbus clouds.

5. Orographic lifting.

No doubt this list could be extended and the relative importance of the various factors assessed by means of a comprehensive synoptic study, but this is beyond the scope of the present paper.

Short notes are given below about each of these factors in turn.

(iv) It has been noticed that the axis of a jet stream frequently coincides roughly with the edge of the cirrus sheet. For this purpose the jet stream speed need not be in the order of 100 knots but merely a wind speed maximum of 50 knots or so. On the cold side there is usually very little high cloud whilst on the warm side cirrus is often extensive. This has also been described by Murray (Ref.5) in a report giving an analysis of jet stream flights made by M.R.F. and by Sawyer and Betty Ilett (Ref.6) in a paper describing a statistical examination of cloud distribution

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near the jet stream. Schaefer (Ref.9) has also associated the occurrence of high clouds with the jet stream in the U.S.A. In our experience the rough boundary of the cloud and no-cloud areas at the jet stream axis is most well marked with jet streams containing a considerable northerly component, cirrus then often being present over western and not over eastern districts of the British Isles.

(v) The classical conception of warm fronts has always included cirrus cloud well ahead of the surface front and in fact it has been found that it can often be associated with surface fronts up to 1,000 miles away. Between the 500 and 300 mb. levels this situation usually shows advection of a warm ridge. The nature of this mechanism by which the necessary cooling for condensation occurs with this warm advection is not fully understood. It was formerly thought to be due to general up-slope motion on the frontal surface but this picture is complicated by the presence of the jet stream which is so often present in the upper troposphere near the junction of air masses, and it is now thought by some authorities that frontal surfaces in fact do not usually extend up to cirrus levels. If the cirrus formation is related to warm advection in this way when warm surface fronts are present there appears to be no prima facie reason why it should not occur when they are absent provided that the situation in the 500-300 mb. layer is broadly similar. A short study of synoptic cases suggested that this is almost always so and warm front cirrus formation may be regarded as a particular case of cloud produced by warm advection in the upper troposphere. In the cases where the connection was not obvious it appeared that the cloud was usually ahead of the main warm advection area. Cold advection and areas of no high cloud appear to be similarly related.

There is considerable support for this idea in general in Ref.(8). The results of M.I.T. Pressure Change Project showed that there was a strong correlation between the sign of the vertical motion and the sign of the temperature advection at 700 mb. and above, warm air advection being positively correlated with ascending air and conversely.

It is also shown in Ref.(7) that changes in the thickness of the 1,000-700 mb. and the 700-500 mb. layers due to advection are largely offset by those due to dynamic heating or cooling or non-adiabatic processes. This compensation was found to be more complete in the higher layer. If this conclusion can be extended to the 500-300 mb. layer it appears quite feasible that warm advection there can be related to a process resulting in dynamic or other cooling and hence a tendency for high cloud to form.

(vi) It was also noted that cold pools and deep troughs on the 500-300 mb. chart are often accompanied by large areas of high cloud. In the case of the troughs the high cloud is generally to the east and south-east and is often associated with warm advection round the south of the trough. With cold pools the high cloud is often more widespread.

(vii) Cirrus cloud may of course often be formed from the tops of cumulonimbus clouds. In such a situation it is often patchy and localised. The cirrus found in conjunction with cold fronts is frequently of this type and is usually not extensive.

(viii) Orographic lifting has also been suggested as a mechanism for forming cirrus cloud (Ref.2). It can be demonstrated however that the conditions when this can occur are somewhat limited. From Ref.(1) it appears that on the average, i.e. including cirrus and non-cirrus cases, the depression of frost point with respect to

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temperature at cirrus levels is about 10 to 12°F. Our Fig.9 shows a mode of 2 or 3°F. depression in and around cirrus cloud. Therefore a temperature loss of 8° or 9°F. due to orographic lifting to reach saturation with respect to ice is usually necessary. For saturation with respect to liquid water the cooling would have to be about another 6°F. i.e. about 15°F. in all. With adiabatic conditions of lifting, therefore, an upward displacement of about 3,000 feet would be required on the average and often considerably more to produce cirrus by the orographic mechanism. In general a lift of 1,000 to 2,000 feet would only be exceeded infrequently and the air at cirrus levels would have to be almost saturated with respect to ice for it to be effective in producing cloud. It is thought therefore that this mechanism would be effective only on the occasions when there is a "moist layer" i.e. usually in air of recent Atlantic track, and either on the warm side of a jet stream, in the vicinity of a cold pool or ahead of a warm front or other warm advection. The effect of orographic lifting would then be most evident in cases where high cloud would be expected from these other considerations and would usually either advance its onset or produce local thickening in the cirrus layer. All the cases discussed in Ref.(2) can be explained on these grounds.

(ix) Although the above factors are helpful in assessing the likelihood of high cloud occurrence there are many synoptic situations when they cannot be used. Cases with no jet stream or cold pool and thickness lines parallel with the wind directions or contours are difficult to assess as also are those associated with small thickness gradients or with concentric contours and thickness lines. The cirrus cloud in inverted situations with contour or thickness highs to the north of the British Isles are often difficult to explain by the above factors. A further study preferably on a statistical basis of the occurrence of high cloud with relation to these and other synoptic factors will be necessary before high-cloud forecasting can be achieved with confidence in these latter situations.

(b) Condensation trails. Condensation trails are usually formed at high cloud levels and they may be regarded as a form of high cloud. Their process of formation is of course an artificial one but once they are formed their behaviour is governed by the same processes as for natural cloud. Thus if atmospheric conditions are such that cirrus cloud is present we might expect condensation trails at the same level to be persistent. Furthermore if the moisture content of the air is large the trails are likely to be longer and of greater duration than if it is small.

These considerations have been examined with respect to the contrails and clouds observed on the high level ascents and the results are presented in Fig.12. Frequency distributions of contrail persistence on occasions of cirrus, distant cirrus, and no cirrus are given. The diagrams illustrate the following points:-

1. When cirrus cloud is present very persistent contrails are the rule. The frequency of 65% given for Contrails Type 7 (very persistent) is almost certainly low. The reason for this is that on occasions it may happen that cirrus is present at lower levels than those at which it is possible for the condensation trails to form from considerations of the relative positions of the temperature sounding and the "Immunity Line" on the Te-Phi-Gram.

2. When distant cirrus or no cirrus is reported very persistent contrails are rare (less than 10%).

/3.

3. The mode for the no cirrus diagram is Type 3 Contrails and that for distant cirrus Type 4. - the latter being the longer. It has been shown above that distant cirrus is usually associated with a moist layer and therefore it appears that the length of a non-persistent trail is a function of the humidity.

Our experience up to the present has provided the following information on which forecast of contrails can be based:-

(a) Contrails normally form for piston-engined aircraft (e.g. a Mosquito) at an ambient temperature of about 12°F. below the Immunity Line (Mintra) as printed on the present Meteorological Office's Te-Phi-Gram (Form 2810A), irrespective of humidity. For jet aircraft it appears from the relatively few experiments that we have yet made that the corresponding figure should be -19°F. i.e. jet aircraft will normally start to form contrails at about 2,000 feet (depending on the lapse rate) higher than a piston engined aircraft. These figures are only averages and may be varied a few degrees by the engine setting of the aircraft. Under suitable marginal conditions contrails can be switched on or off by varying throttle settings.

(b) If cirrus is present and the difference between the Mintra line and the ambient temperature is sufficient for the contrails to form then they will be very persistent at the high cloud level. At other levels they will be non-persistent but if the cirrus cloud coincides with the start of the contrails, then they will be persistent immediately without having a layer of non-persistence below.

(c) Contrails normally appear to start becoming shorter just above the tropopause and short trails have still been observed several thousand feet into the stratosphere. More precise information on the conditions at which contrails finally stop in the stratosphere has not yet been obtained owing to the limited ceiling of the aircraft so far available.

As very persistent contrails are more easily visible from the ground than thin cirrus, then, when the former are observed, it can be assumed that the latter is present in extensive sheets even though it cannot be seen from the ground.

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(3) 1952. Farquharson, J.S. Met.Mag., Vol. 81, p.341.

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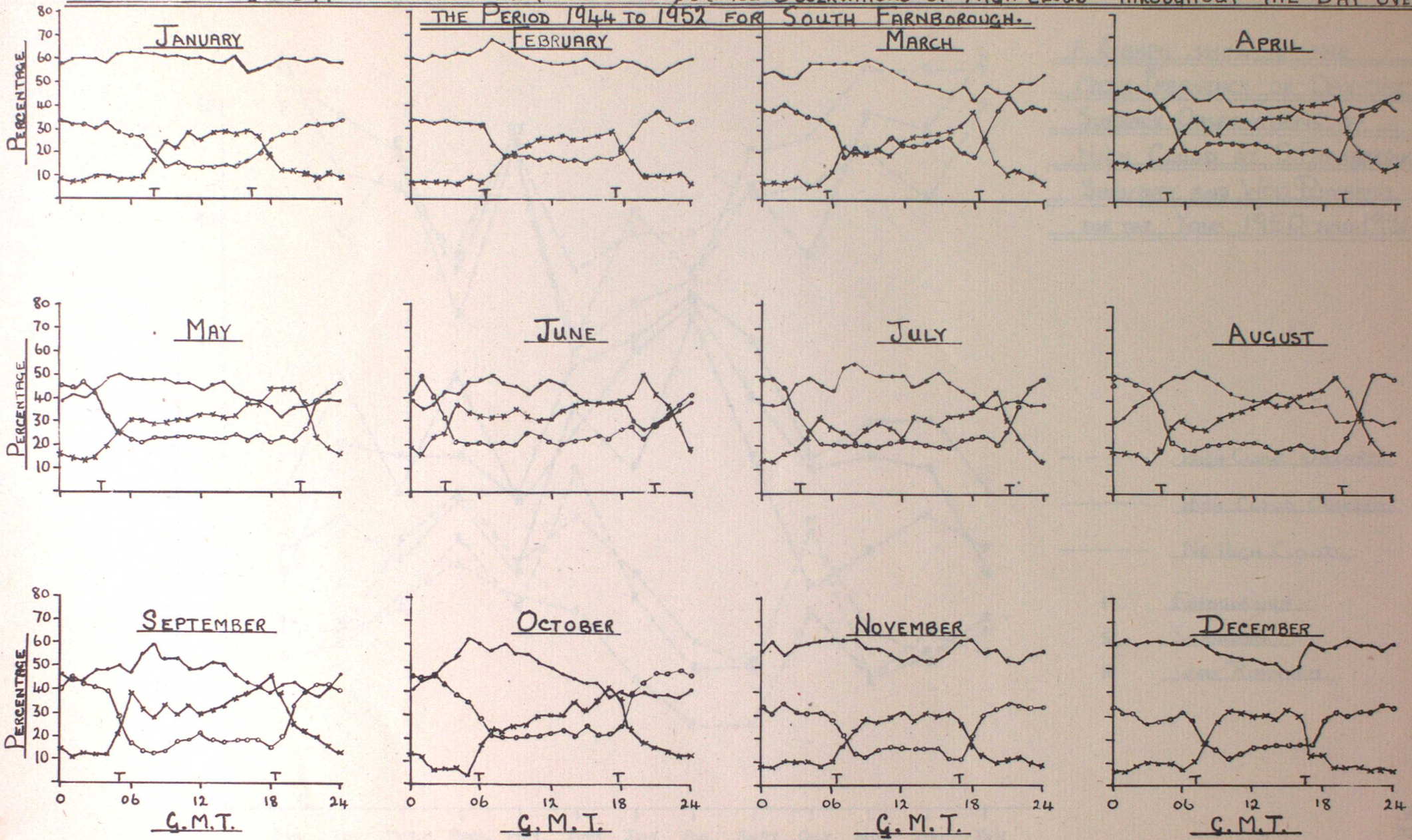
(9) 1953. Schaefer, V.J. Tellus, Vol. 5, No.1.

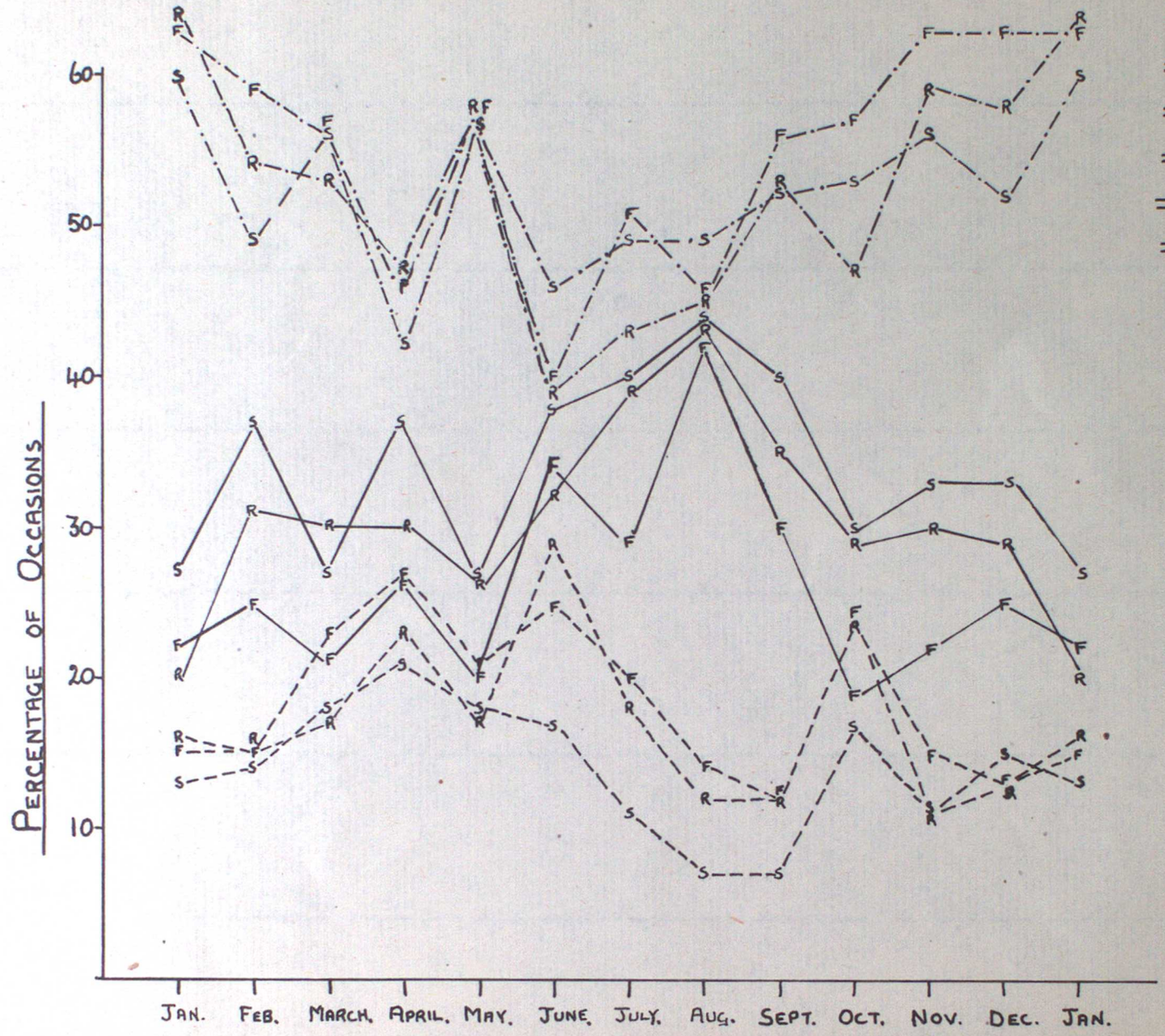
GRAPHS SHOWING THE MEAN MONTHLY FREQUENCIES OF SURFACE OBSERVATIONS OF HIGH CLOUD THROUGHOUT THE DAY OVER THE PERIOD 1944 TO 1952 FOR SOUTH FARNBOROUGH.



T. DENOTES THE APPROXIMATE TIMES OF TWILIGHT.

FIGURE 1. HIGH CLOUD OBSCURED, NO HIGH CLOUD, HIGH CLOUD OBSERVED.

M.R.P. 833.



A GRAPH SHOWING THE MEAN FREQUENCY OF DAY-TIME SURFACE OBSERVATIONS OF HIGH CLOUD AT S. FARNBOROUGH, SHAWBURY AND WEST RAYNHAM FOR THE YEARS 1950 AND 1951.

-.-.-.- HIGH CLOUD OBSCURED.

——— HIGH CLOUD OBSERVED.

- - - - - NO HIGH CLOUD.

F FARNBOROUGH.

S SHAWBURY.

R WEST RAYNHAM.

FIGURE 2.a.

M.R.P. 833.

A GRAPH SHOWING THE MEAN FREQUENCY OF DAY-TIME SURFACE OBSERVATIONS OF HIGH CLOUD AT S. FARNBOROUGH FOR THE YEARS 1944 TO 1952.

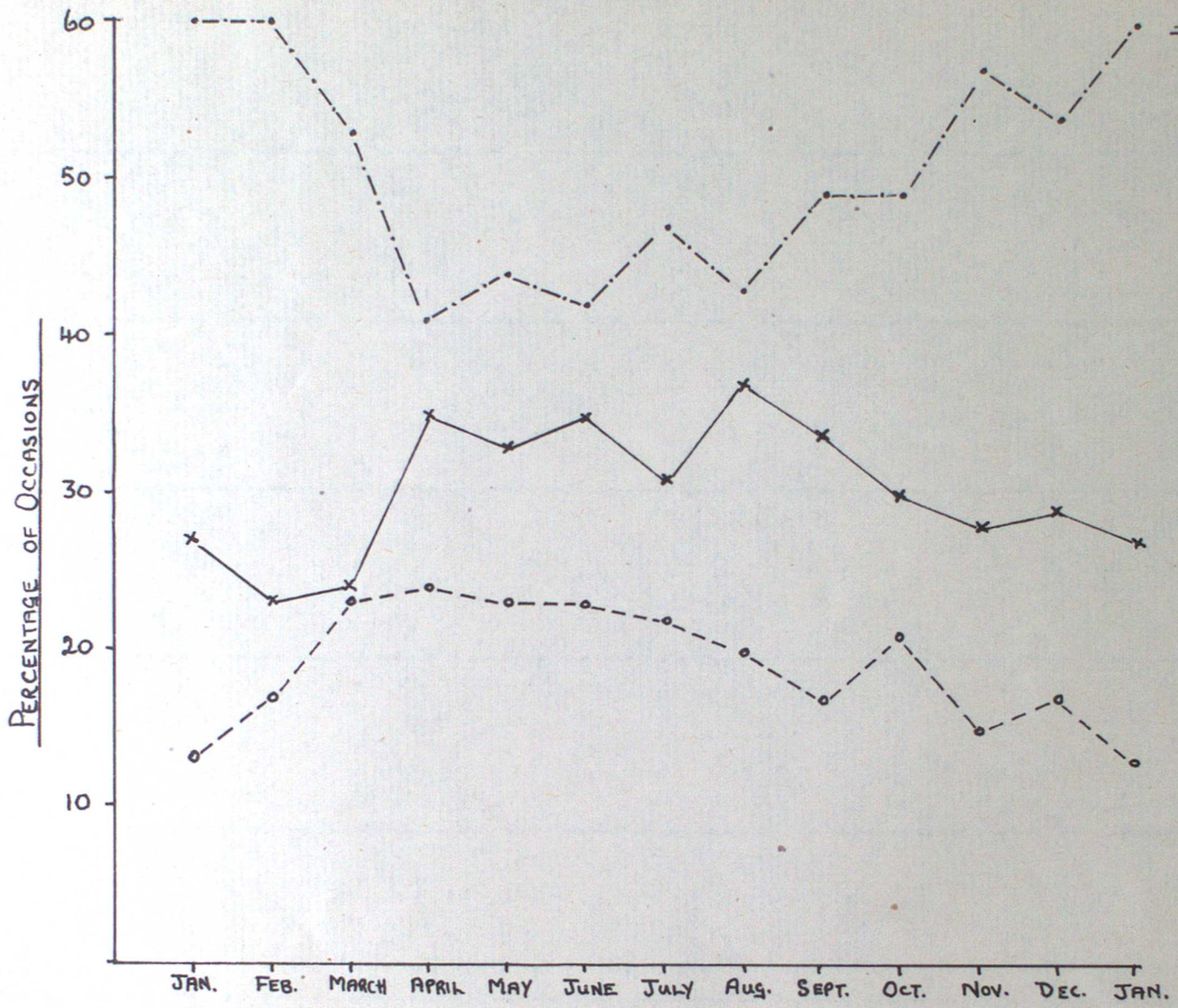
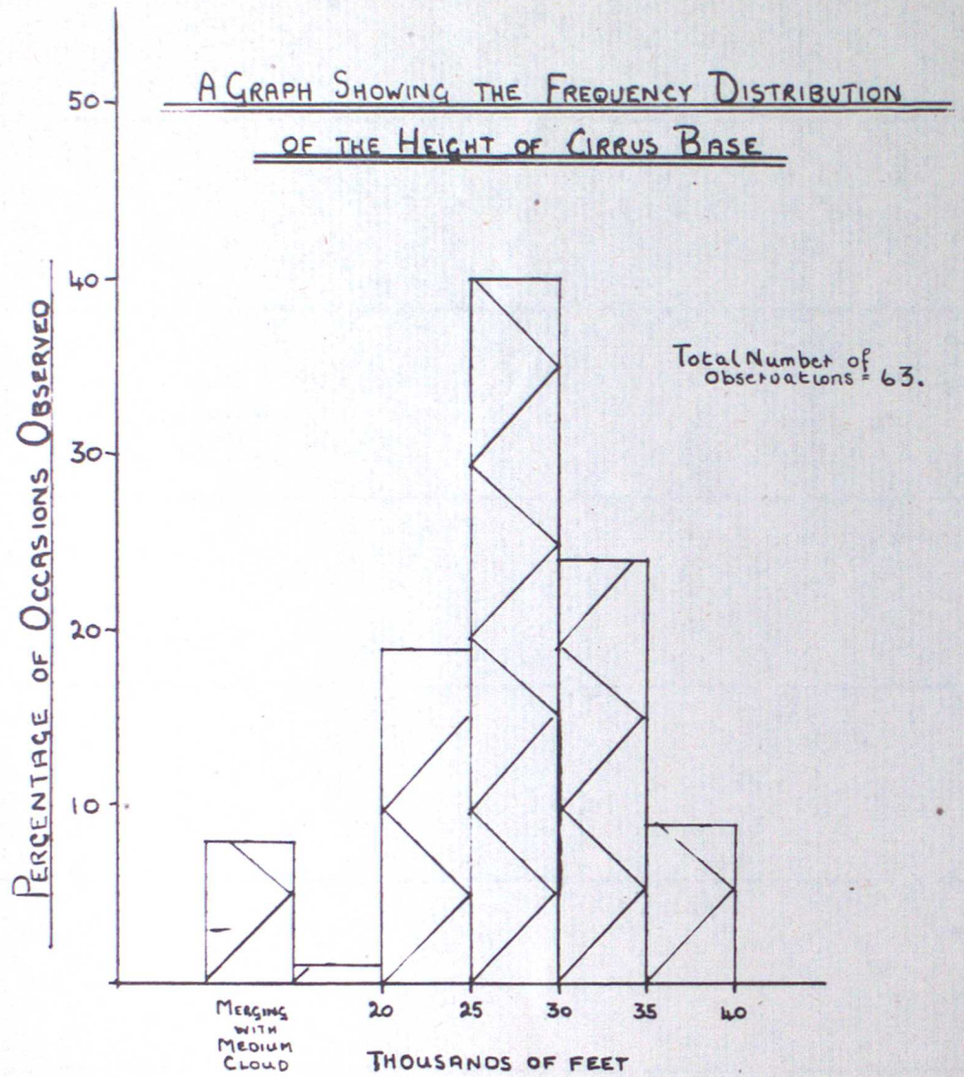


FIGURE 2.b.

M.R.P. 833.

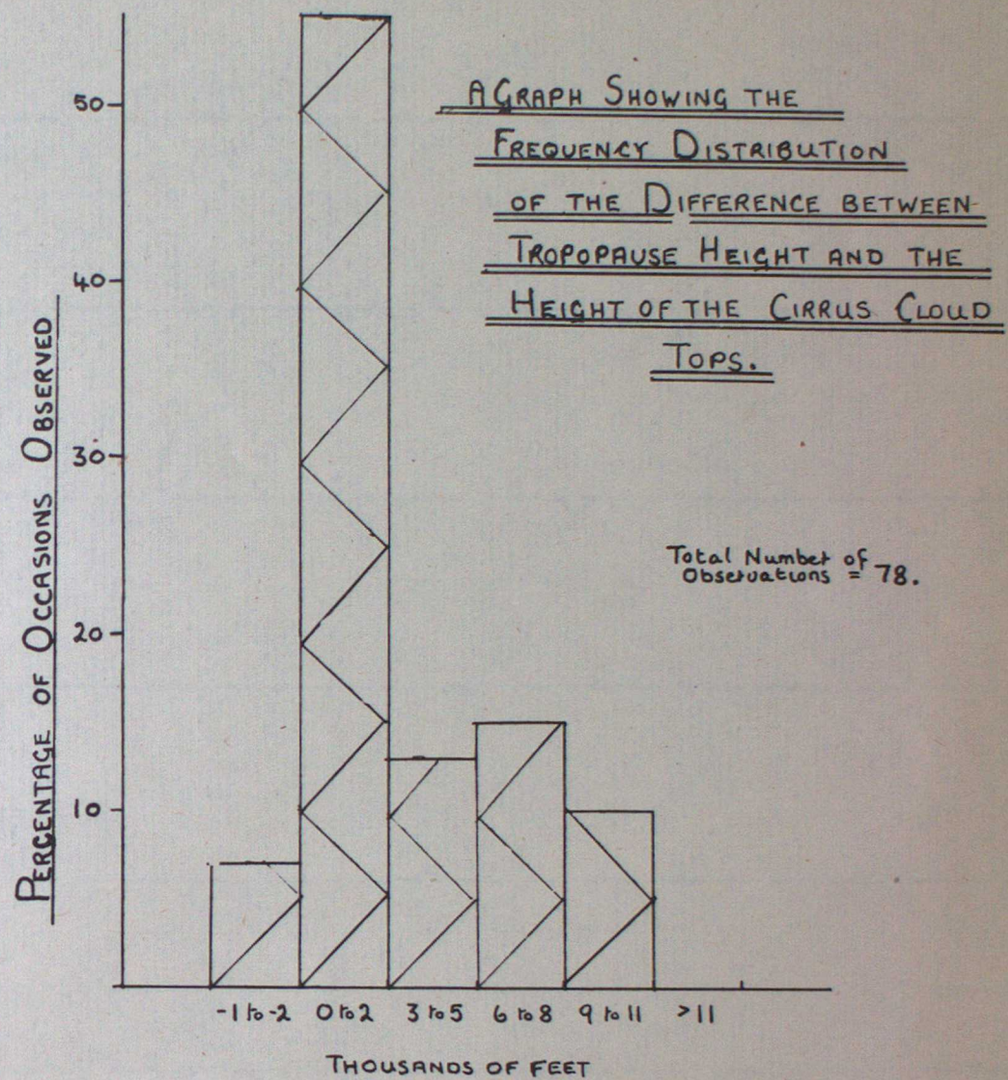
A Graph Showing the Frequency Distribution of the Height of Cirrus Base



The Height of the Cirrus Base.

Figure 3.

A Graph Showing the Frequency Distribution of the Difference between Tropopause Height and the Height of the Cirrus Cloud Tops.



The Difference between the Height of the Tropopause and the Height of the Cirrus Cloud Tops.

Figure 4.

M.R.P. 833.

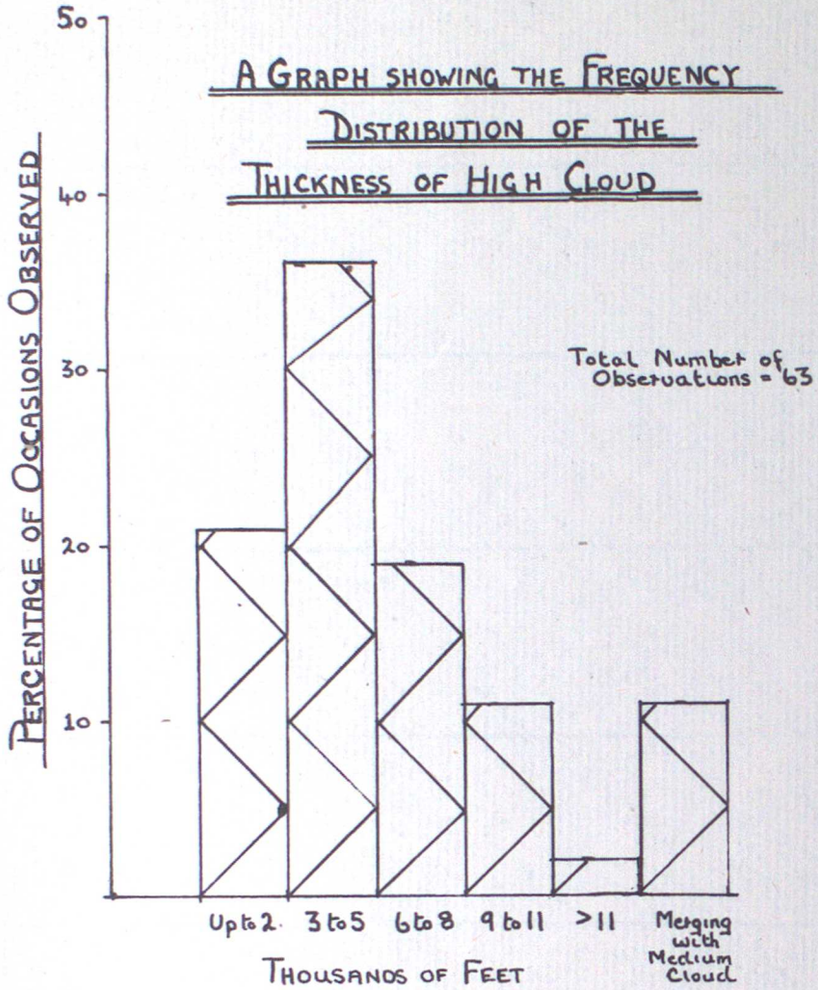


Figure 5.

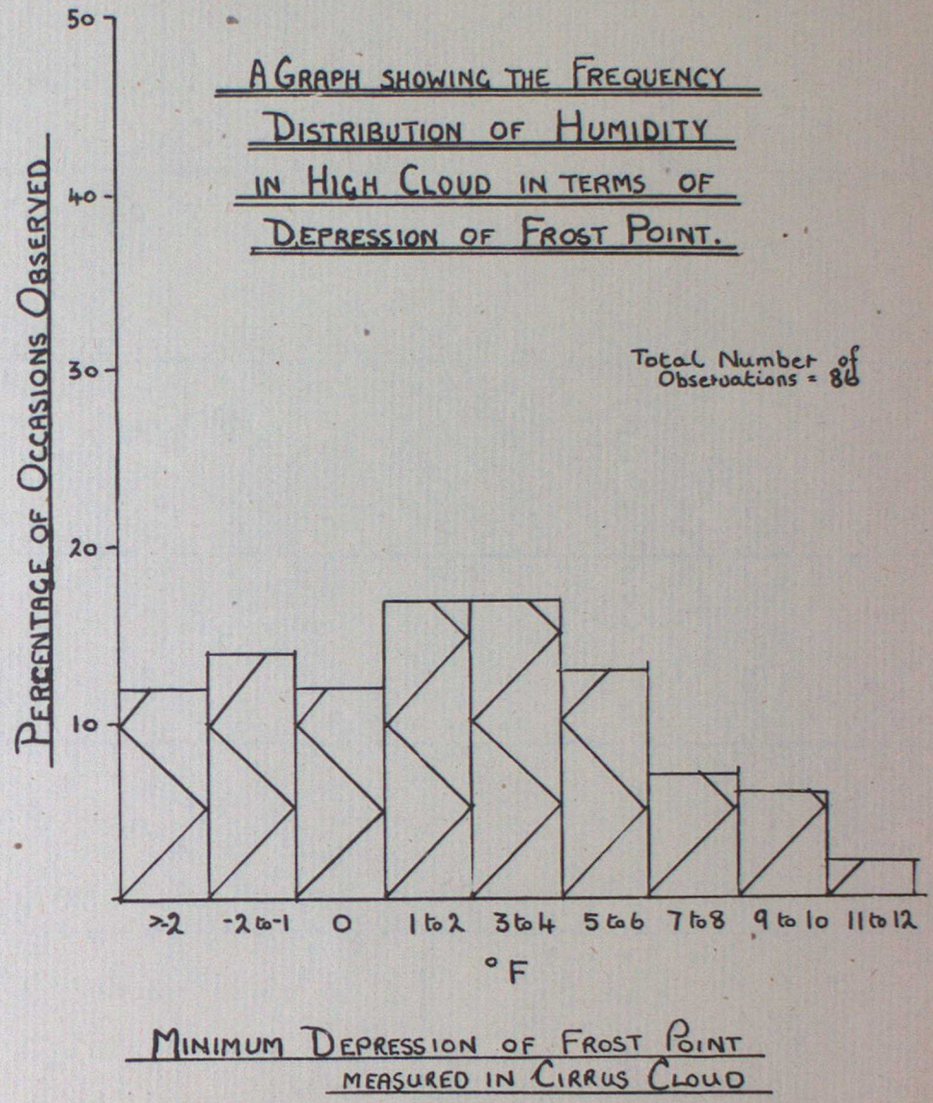


Figure 9.

M.R.P. 833.

A Graph Showing the Frequency Distribution of the Temperature of the Base of Cirrus Cloud

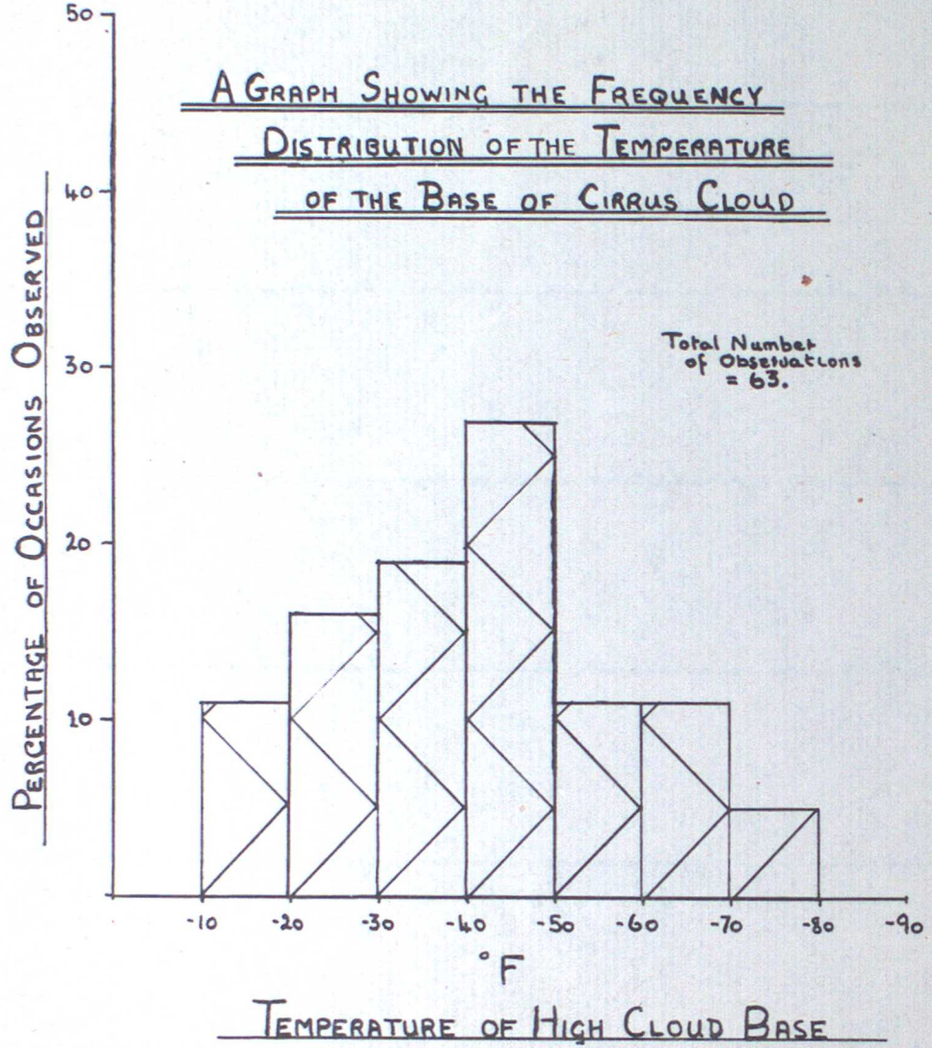


Figure 7.

A Graph Showing the Frequency Distribution of the Temperature of the Tops of Cirrus Cloud

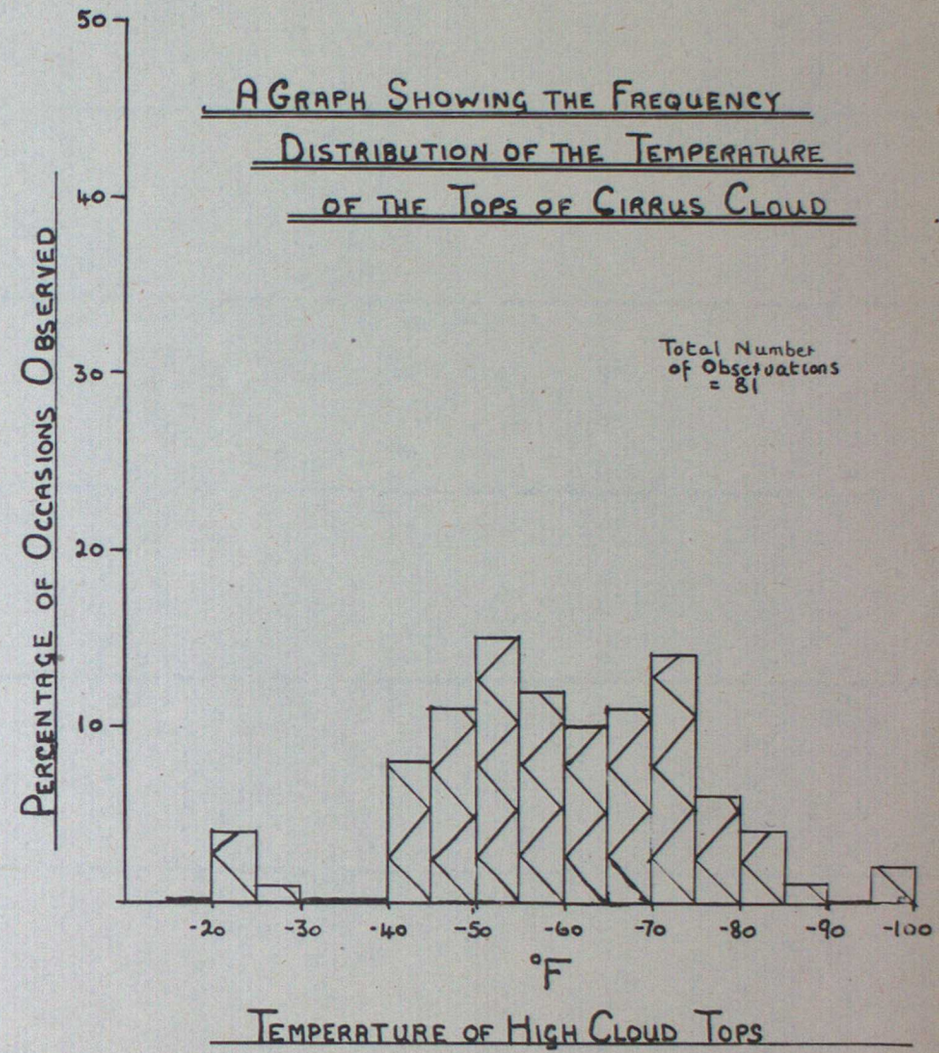


Figure 8.

M.R.P. 833.

Three Aircraft Soundings, Illustrating the "Moist Layer" Effect

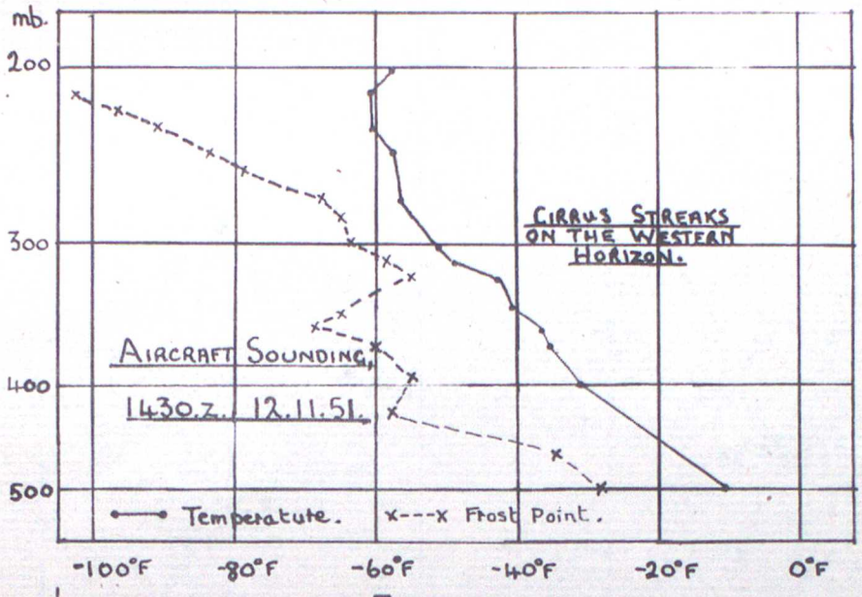


Figure 10.A.

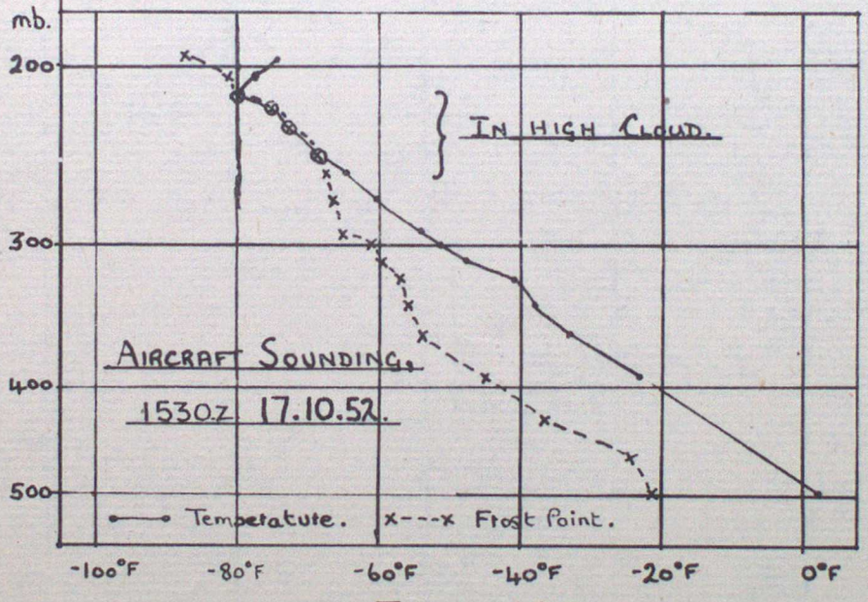


Figure 10.B.

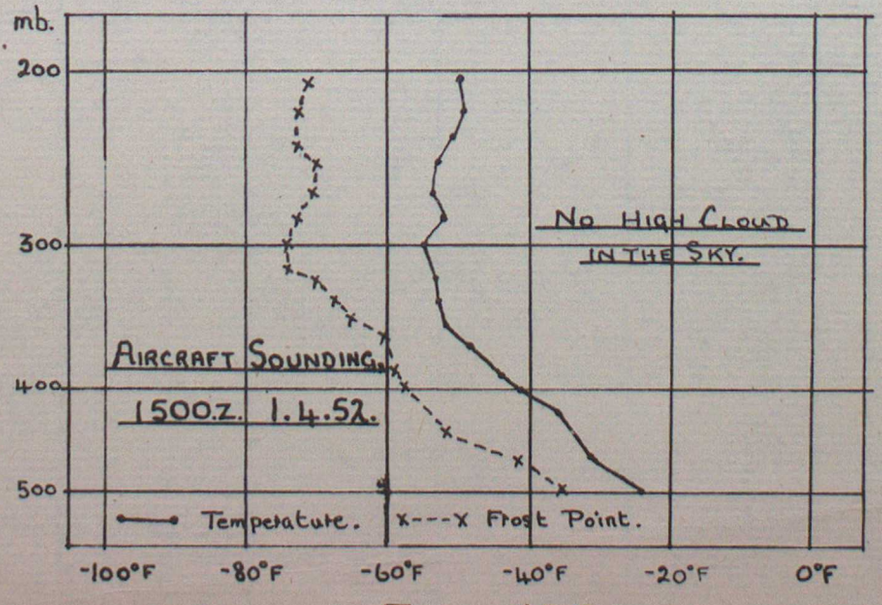


Figure 10.C.

A Graph of the Heights of the Moist Layer Base and Tops plotted against the Height of the Tropopause.

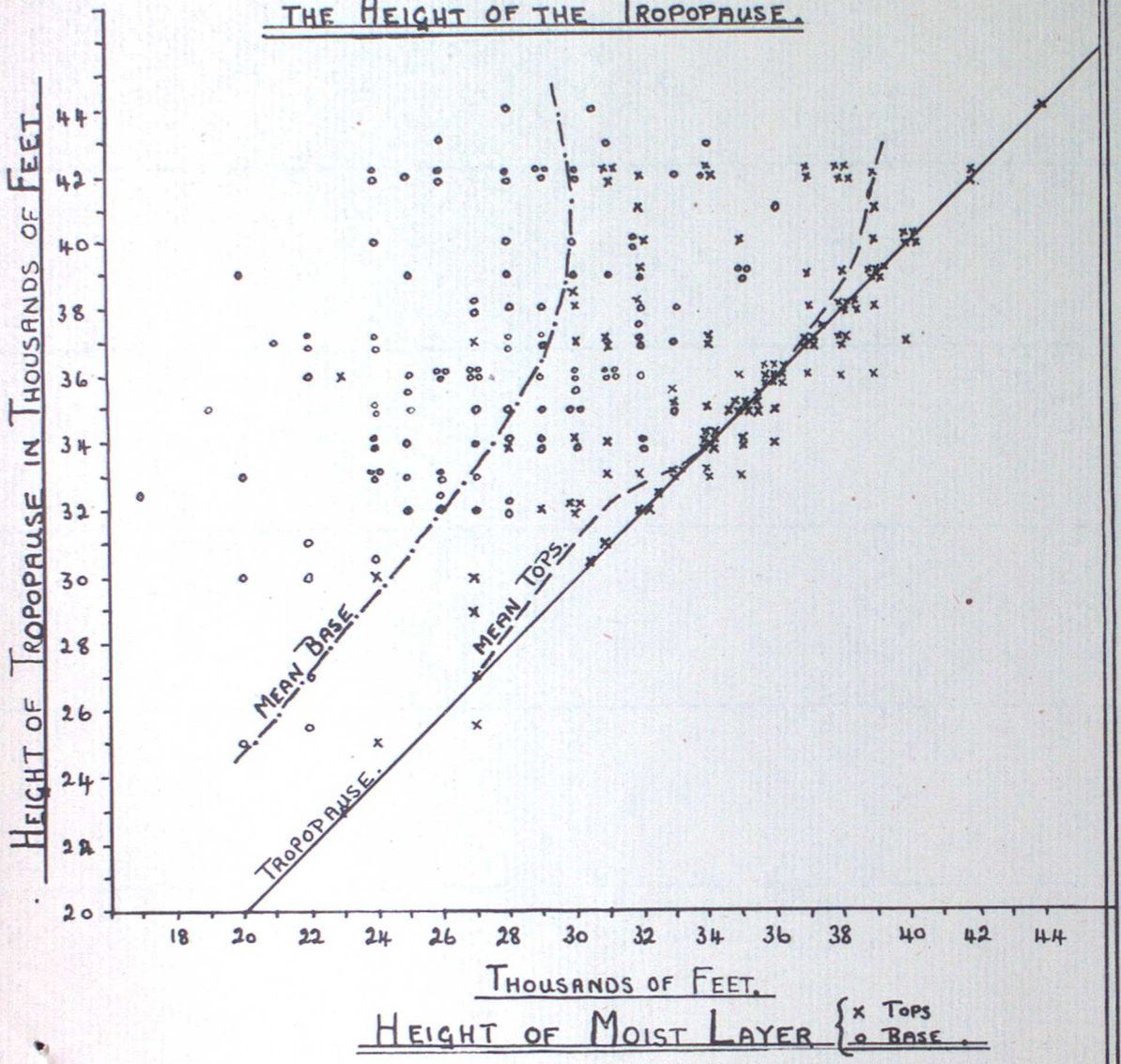


Figure 11.

A Graph of the Heights of High Cloud Base and Tops plotted against the Height of the Tropopause.

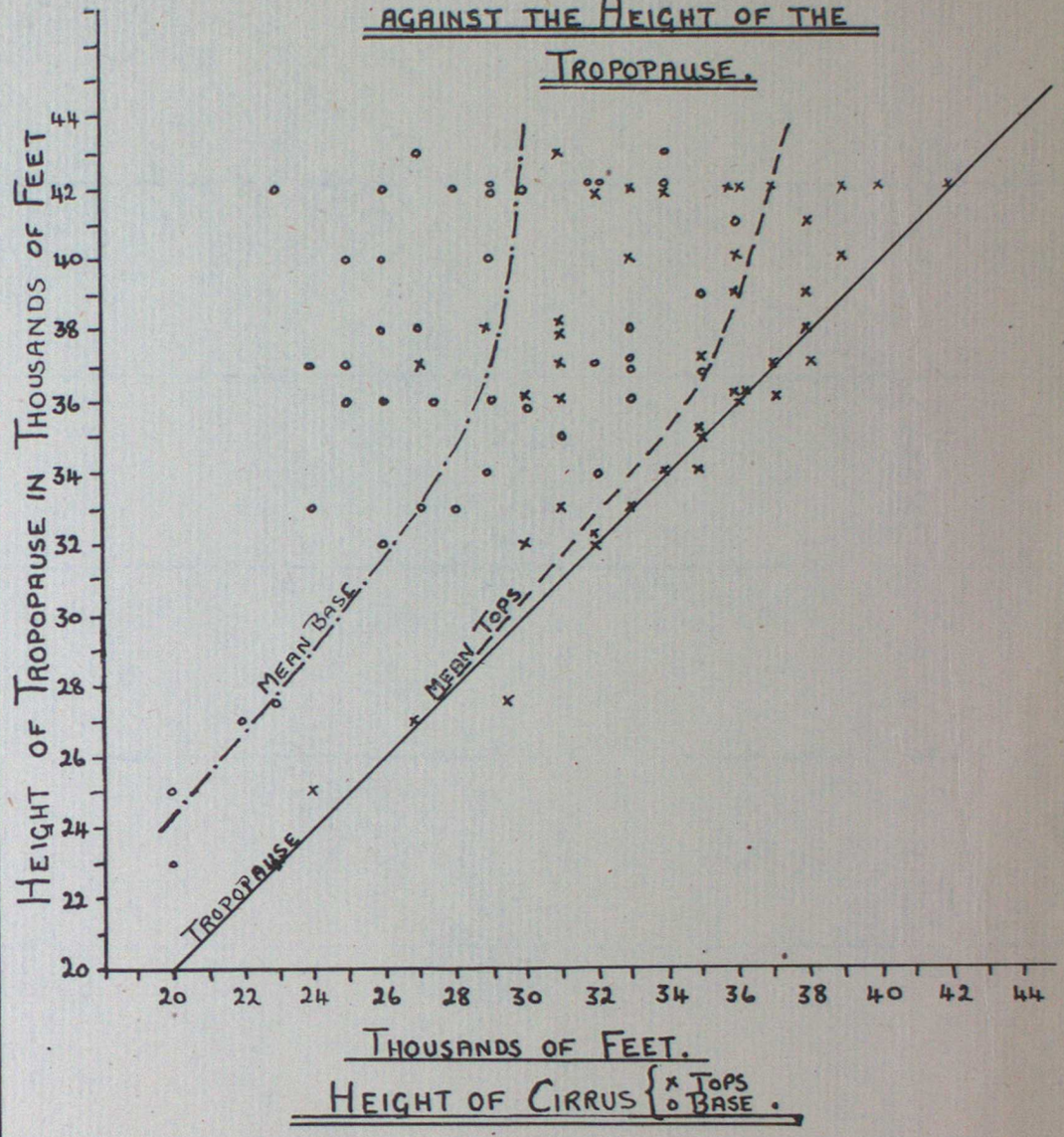


Figure 6.

M.R.P. 833.

Graphs showing the Frequency Distribution of the Degree of Persistence of Contrails Observed on Flights when:-

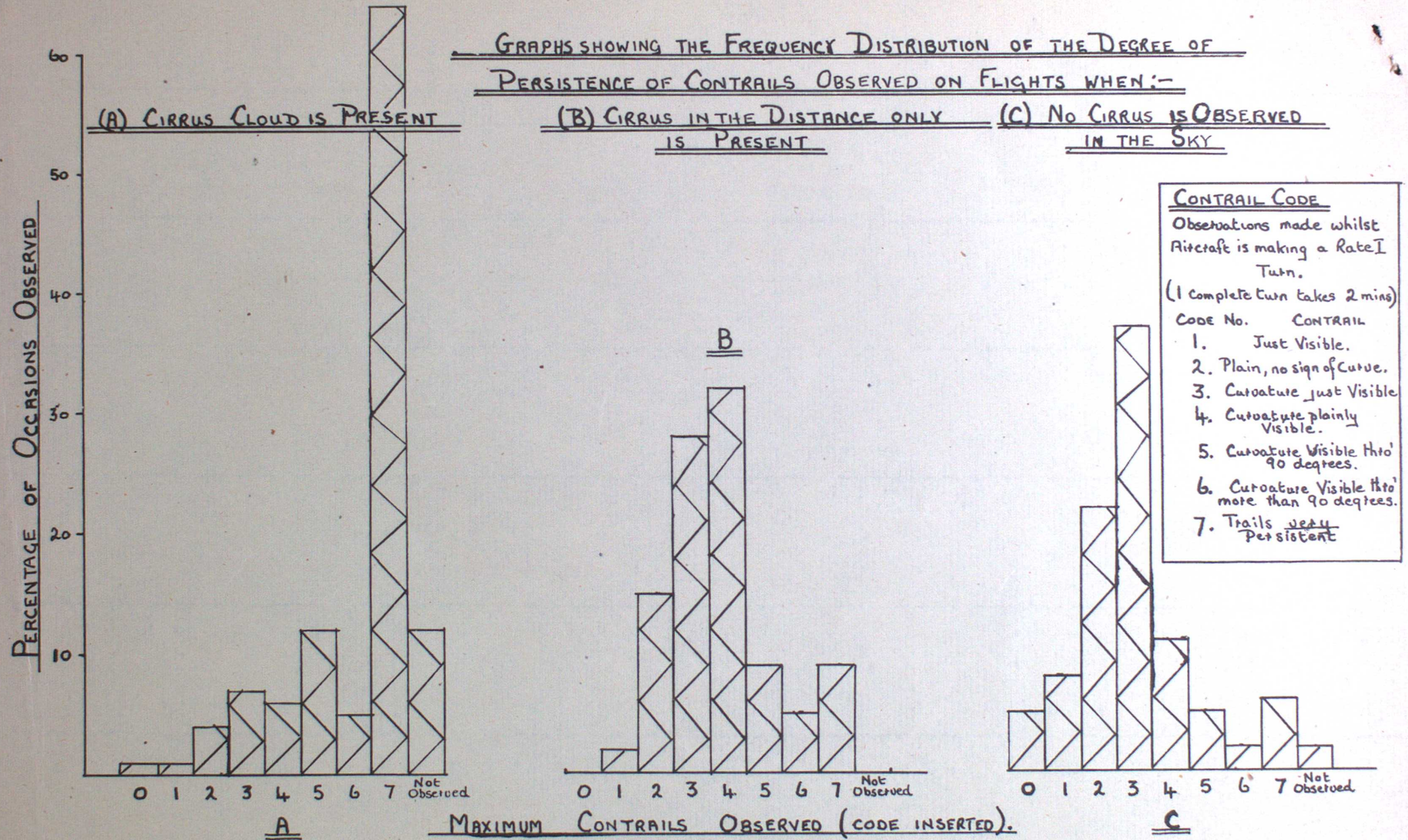


Figure 12.

M.R.P. 833.